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THE EFFECTS OF SURFACE LAYER ON PLASTIC DEFORMATION AND CRACK PROPAGATION

January 1972

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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13. ABSTRACT

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FOREWORD

This report was prepared by the Denver Division of Martin Marietta Corporation under U. S. Army Contract DAAG 46-70-C-0102. The contract is sponsored by the Advanced Research Project Agency under ARPA Order 188-0-7400 and is being administered by the Army Materials and Mechanics Research Center, Watertown, Massachusetts, with Dr. Eric B. Kula, AMXMR-RM, serving as Technical Supervisor.

This project has been accomplished as part of the U. S. Army Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques or equipment to insure the efficient production of current or future defense programs.

ABSTRACT

A change in proportional limit after cycling was observed for aluminum 2014-T6. Cycling below the endurance limit increases the proportional limit. However, when the surface layer was eliminated by relaxation, the proportional limit was restored to its original value. These data show that the work hardening is confined mainly in the surface layer. The etch pit distribution of dislocations in Fe-3Si steel was investigated. The threshhold stress for the appearance of slip steps in untreated and SSLE treated specimens of aluminum 2014-T6 was determined. The percent of grains deformed in specimens of aluminum 2014-T6 which are stressed to various values was observed. The effect of SSLE treatment on the threshhold stress intensity for 4130 steel was established. A diametral gage to measure the surface layer stress of notched specimens was manufactured.

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I. INTRODUCTION

Under this contract we are investigating the effect of surface layer on the rate of crack propagation and based on this knowledge, we propose to improve the crack propagation resistance of metals. During the past year it has been shown(1) that prestress and surface layer elimination (SSLE) treatment decreases the rate of crack propagation in titanium (6Al-4V), 4130 steel and aluminum 2014-T6. The measurements were carried out under plane stress as well as under plane strain conditions. In many applications, structures are loaded under cyclic conditions and a pre-existing flaw propagates slowly until it reaches the critical value and catastrophic failure takes place. Therefore, the subcritical growth of cracks is very important in fracture mechanics.

From the evidence accumulated from cycling behavior and by purposely increasing or decreasing the surface layer stress, a hypothesis for fatigue cycling failures has been formulated.(2) This hypothesis is based upon dislocation reactions that take place within the surface layer. It is proposed that during cycling the surface layer stress increases and when the surface layer becomes sufficiently strong to support a "pile up" and the stress increases locally above the fracture strength, a crack is formed. This crack will propagate until the local stress is reduced below the fracture stress. During the next cycle the surface layer stress will be increased and the crack will again propagate. This process will give rise to steps on the fractured surface in accordance with observations. On the basis of this hypothesis, the endurance limit would be that stress amplitude at which the surface layer did not form, or the rate of increase of the surface layer is very small and does not build up to a critical value during the fatigue test. A reduction in the surface layer stress reduces the rate of crack propagation. The surface layer stress is increased under corrosive environment. A strong film formed as a result of the reaction products of metal and active species in the environment would tend to enhance the formation of the surface layer and decrease its relaxation. Further, an environment which in some way embrittles the surface layer would decrease the fracture toughness and increase the rate of crack propagation. This statement follows from the fact that in practically all cases, the crack passes through the surface. Normally, during fracture, considerable plastic deformation occurs in the region close to the exterior surface and as a result the crack propagation rate at these sites is less than that in the interior. This difference causes the crack profile to have a thumbnail shape. Any reduction in ductility in the surface layer by embrittlement will reduce the fracture

toughness. The decrease in the rate of crack propagation when the surface layer is reduced follows the same behavior as that of the fatigue life. When the specimens are prestressed and the resulting surface layer is removed, it does not reform until the stress in front of the notch or crack is approximate equal to that of the prestress σ_{ps}. Actually the reformation of the surface layer should begin at $\sigma_{ps} - \sigma_s$ where σ_{ps} is the prestress. Accordingly, it would be expected that the improvement in the crack resistance would be highest at low ΔK values and the improvement would diminish at high ΔK value.

II. EXPERIMENTAL RESULTS AND DISCUSSION

During this period, we have investigated the mechanisms involved in the SSLE treatment. The etch pit distribution of deformation bands in Fe-3Si steel was investigated. The change in proportional limit after cycling was observed for aluminum 2014-T6. The threshhold stress for the appearance of slip steps in untreated and SSLE treated specimens of aluminum 2014-T6 was determined. The percent of grains deformed when specimens of aluminum 2014-T6 are stressed to different values was observed. The effect of SSLE treatment on the threshhold stress intensity for 4130 steel was established. A diametral gage to measure the surface layer stress of notched specimens was manufactured. Specimens with suitable stress concentration factors were designed and machined out of titanium (6Al-4V). These topics are described in detail.

A. ETCH PIT DISTRIBUTION IN SILICON IRON

There have been several attempts to measure the dislocation density by means of etch pit and thin film electron microscopic techniques. Kitajima[3] reported that the dislocation density of strained copper single crystals was highest at the surface and the density decreased to a constant value after a depth of about 50-100 microns. Suzuki[4] reported a surface layer of about 50 microns in deformed KCl crystals. These values agree with those obtained by measuring the surface layer stress. Vellaikal and Washburn[5] also reported that in polycrystalline copper plastic flow occurred first in the surface grains and then in the bulk. In contrast, Block[6], ostensibly using the same technique as Kitajima, reported that the dislocation density was uniform throughout the cross section of strained copper crystals. Fourie[7] deformed

copper crystals and, by an electrochemical jet technique, cut out specimens 0.003 inches thick. He reported that the outer portions of the strained specimens were softer than that of the bulk. These data would imply that the initial flow stress would be above the unloading stress for specimens which are deformed and the surface layer removed. The data would also imply that the activation energy would increase and the activation volume would decrease when the measurements were taken under continual metal removal conditions. It has been shown(8) that for aluminum, copper and gold, the apparent activation energy for deformation decreases as the rate of metal removal increases.

Hahn, Mincer and Rosenfield(9) at Battelle Memorial Institute have experimented with dislocation etch pits in Fe-3Si steel. They have kindly donated a piece of their alloy approximately 3" x 2" x 0.5". Tensile specimens were made. The dog bone shaped specimens were annealed at 1436°F followed by forced-air cooling to room temperature. The specimen was successively stressed to the proportional limit and at higher stresses followed by aging at 150°C for 20 minutes. The specimens were then polished and etched in Morris solution to reveal deformation bands. The Morris solution consists of 7 cc of H_2O, 25 g chromium trioxide, 133 cc glacial acetic acid. Electropolishing was done in the range 22-40 volts with the solution maintained at 20°C. Etching occurs at about 5 V in 3-15 minutes without agitation.

The metallographs of Fe-3Si steel which has been stressed to 50 Ksi, aged, polished and etched are shown in Figure 1. The specimen was polished to remove 0.001 in. from the surface and re-etched. It is observed that the dislocation density is much reduced. The same specimen was pulled to 1% plastic strain followed by aging and etching. The dislocation density is shown in Figure 2. The specimen was polished to remove 0.004 in. and was re-etched. The same area is shown in Figure 2. Again, it is observed that the dislocation density is reduced when the surface is removed. The specimen was again strained to 1.5% plastic strain, aged and etched. The results are shown in Figure 3. The specimen was polished to remove 0.003 in. from the surface and re-etched. We observe that removing the surface layer decreases the density of dislocation bands. Thus it is concluded that when Fe-3Si steel is deformed, the dislocation band density is greater in the surface layer than in the bulk.

B. EFFECT OF CYCLING ON THE PROPORTIONAL LIMIT

An investigation was conducted on the effect of cycling below and above the endurance limit on the proportional limit of titanium (6Al-4V). The specimens had a nominal diameter of 0.15 in. and a uniform gage length of 0.3 in. Before testing the specimens were annealed in vacuum at 760°C for two hours. The specimens were polished in nitric-hydrofluoric acid until the diameter was reduced by 0.004 in. The testing was conducted in an electrohydraulic machine (MTS). The proportional limit of the specimens was measured in an Instron testing machine. An extensometer was mounted across the specimen to measure strain. Specimens were cycled in tension-compression below the endurance limit at a stress of ± 55 Ksi for 3 and 5 million cycles. The cycling was carried out at 20 cycles per second. Following the cycling the surface layer was eliminated by relaxation for 2 days. The specimen was pulled in the Instron machine and the proportional limit was measured. The proportional limit was 122,000 psi and is about the same, within experimental error, as the value of 119,114 psi obtained for a specimen which has not been cycled. Another specimen was cycled for 3.5 million cycles and was allowed to relax for 6 days. The proportional limit of this specimen was 123,106 psi.

The increase in surface layer stress upon cycling titanium (6Al-4V) specimens at ± 80 Ksi and at ± 90 Ksi is shown in Figure 4. It is observed that the surface layer stress increases linearly with the number of cycles. If the lines are extrapolated to N_f which is the number of cycles to failure, the corresponding value for σ_s is 35,000 psi. Thus it is shown that cycling increases the surface layer stress and when the surface layer stress reaches a value equal to 35,000 psi, the specimen fails.

C. DEFORMATION OF ALUMINUM 2014-T6

We are attempting to understand the mechanisms involved in the SSLE treatment. Specimens of aluminum 2014-T6 were polished flat for metallographic observations. The specimens were stressed to various stress levels and observed metallographically for evidence of slip lines. The percentage of grains deformed as the specimen is pulled to various stress levels are shown in Figure 5. It is observed that as the stress is increased above 5 Ksi, the percentage of grains deformed rapidly increases. The effect of SSLE treatment on the threshold stress, σ_{th}, was also investigated. The untreated specimen begins to deform at 5 Ksi. A second specimen was prestressed to the proportional limit (60 Ksi). An amount of 0.001 in. was removed from the

surface and the specimen was stressed incrementally until slip lines appeared. The stress at which slip lines appeared (σ_{th}) was 46 Ksi. This procedure was repeated and the value of σ_{th} as a function of depth was determined. It was made certain that adequate amounts of surface had been removed so that slip lines corresponding to the previous deformation disappeared. The data are shown in Figure 6. The data show that the surface region is work hardened to a greater extent than the interior of the specimen. In addition, stressing to the proportional limit work hardened the interior so that the threshhold stress increased from 5 to 34 Ksi.

The effect of prestressing on the threshhold stress for single crystals of aluminum was also investigated. Dog bone shaped specimens of single crystal aluminum were presetressed to 1100 psi. The specimens were then polished to remove 0.002 in. and the threshhold stress for the onset of slip lines was determined to be 900 psi. After removing 0.003 in. from the surface, the threshhold stress reached a plateau at 800 psi and no further decrease was observed with continued removal as shown in Figure 7.

D. THRESHHOLD ΔK

It has been shown previously that SSLE treatment decreases the rate of crack propagation. The minimum ΔK below which the initial flaw does not propagate up to a million cycles has been defined as ΔK_{th}. The effect of SSLE treatment on the ΔK_{th} value of 4130 steel was investigated. For the SSLE treatment of 4130 steel, the specimens were prestressed to 120.5 Ksi and the surface layer was eliminated by relaxation. Center notched specimens which have been previously described were used. The initial flaw which was 0.2" long was put in with a jeweler's saw. In the SSLE treated specimens, the flaw did not start even up to 1 million cycles, while in the untreated specimens the initial crack started to propagate after 200,000 cycles at a stress of 4,250-17,000 psi.

E. SURFACE LAYER STRESS FOR NOTCHED SPECIMENS

In previous work[2] the surface layer stress has been measured on smooth specimens and no data are available on notched specimens. We consider information of the behavior and values of the surface layer in front of cracks and notches important to the understanding of crack propagation. Relaxation methods will be used to measure the surface

layer stress since the chemical removal method would alter the size and shape of the notch. Tensile specimens of titanium (6Al-4V) have been prepared which have notch concentration factors of about 3. The specimens will be strained and then allowed to relax. The difference between the maximum stress during the preload and the initial flow stress after relaxation will be taken as the surface layer stress. The strains will be measured with a diametral gage and the load will always be below that which causes extension of the crack.

The diametral gage has been manufactured and received. It consists of jaws which fit right into the hotch. Two lever arms transmit the change in diameter at the grips to a LVDT. The diametral gage is being checked out for operation.

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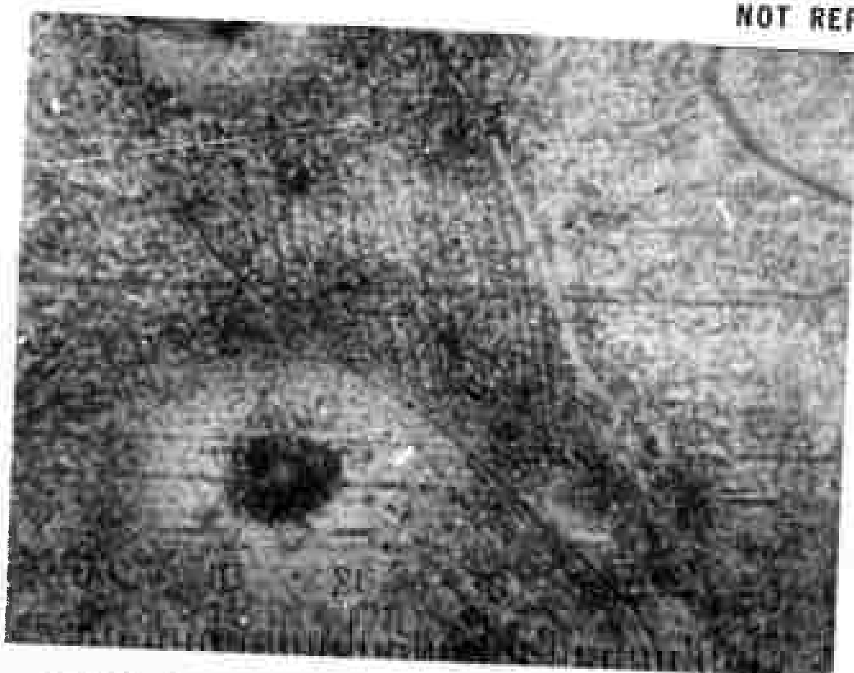
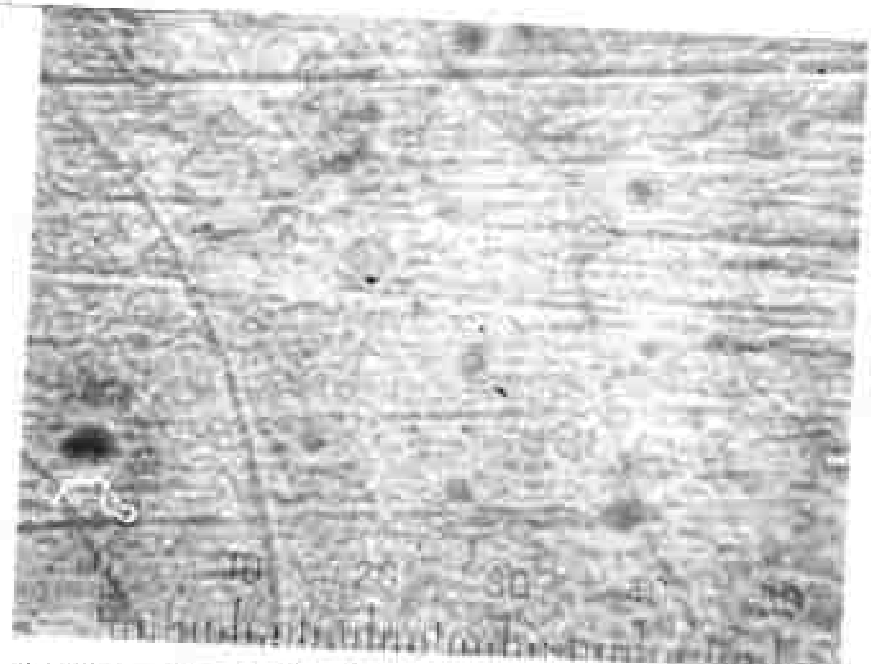
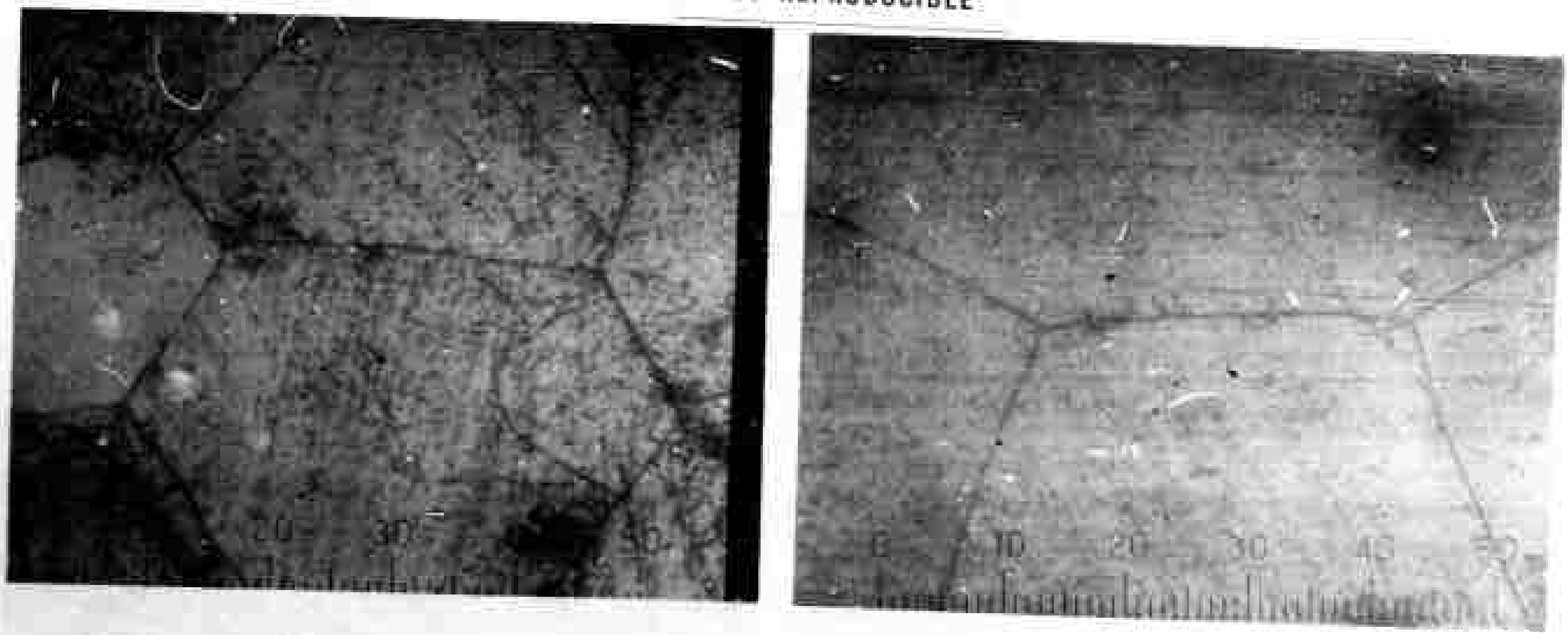


(a) Dislocation Distribution in Fe-3 Si Steel Stressed to 50 ksi, X1200



(b) Same Area As in (a) After Removal of 0.001 in., X1200

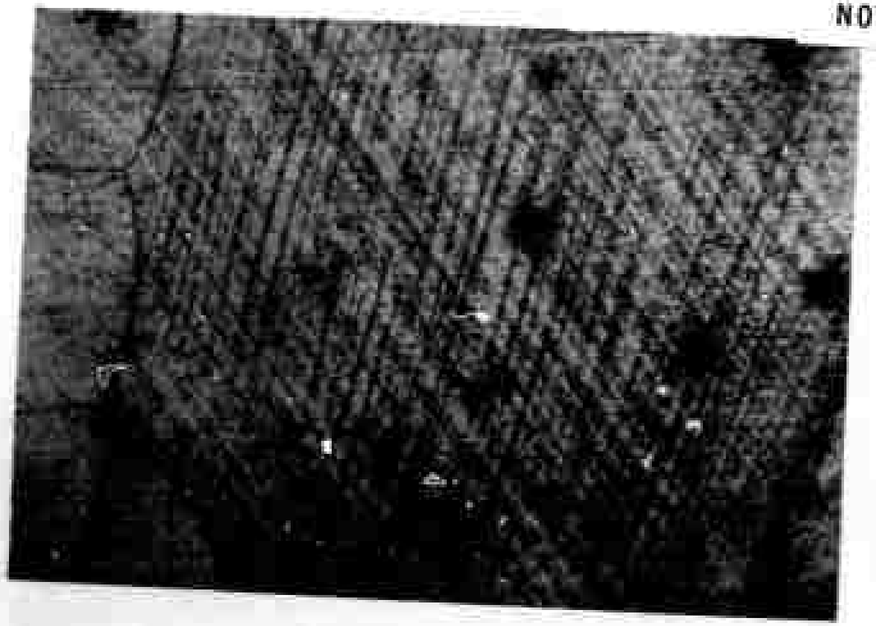
Figure I



(a) Dislocation Distribution in Fe-3 Si Steel Stressed to 1% Strain, X1200

(b) Same Area As in (a) After Removal of 0.004 in, X 1200

Figure 2



(a) Dislocation Distribution in Fe-3 Si Steel Stressed to 1.5% Strain, at Surface X1200

(b) Same Area As in (a) After Removal of 0.003 in., X1200

Figure 3

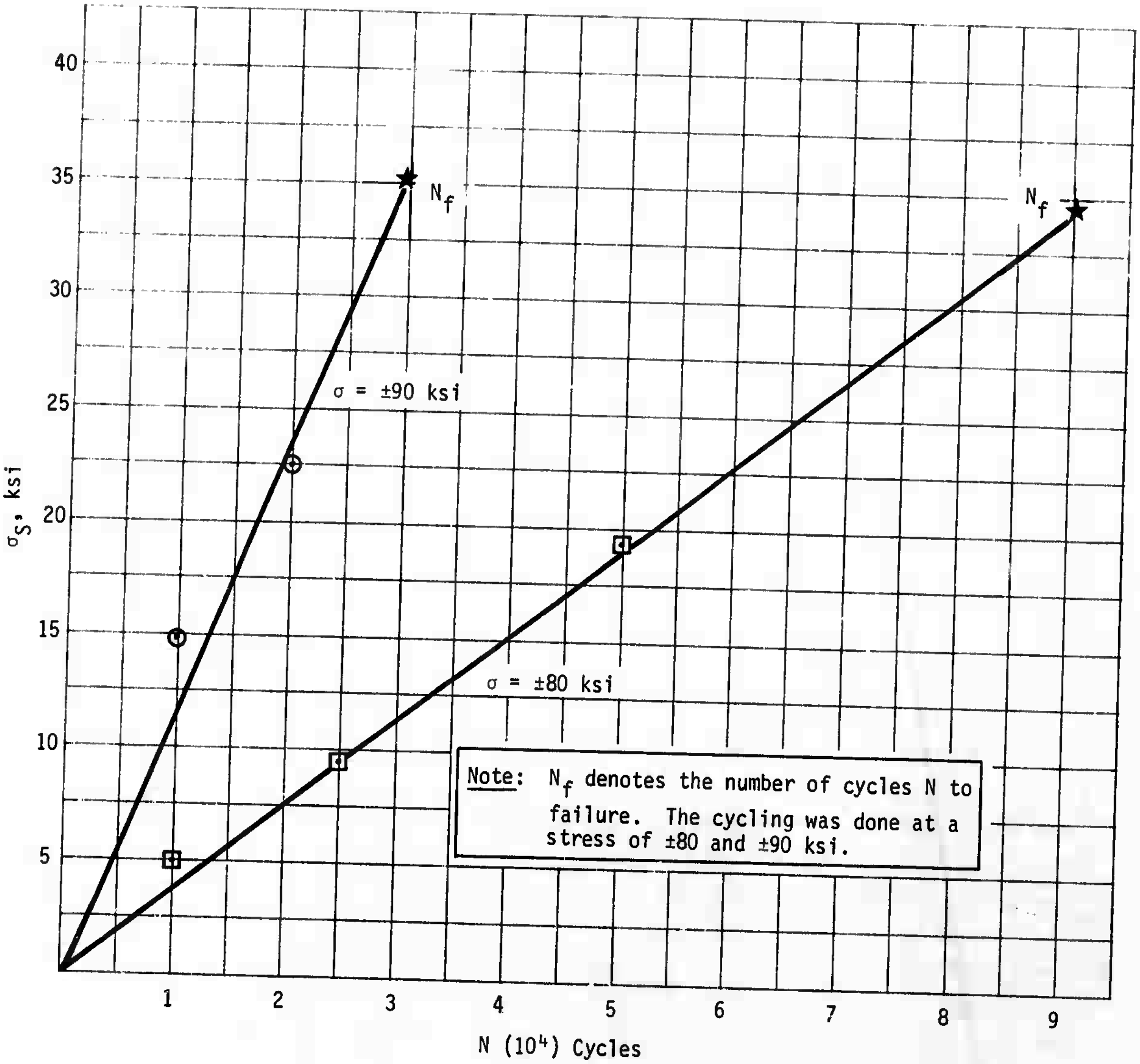


Figure 4 The Increase in Surface Layer Stress σ_S with Cycling for Titanium (6Aℓ-4V)

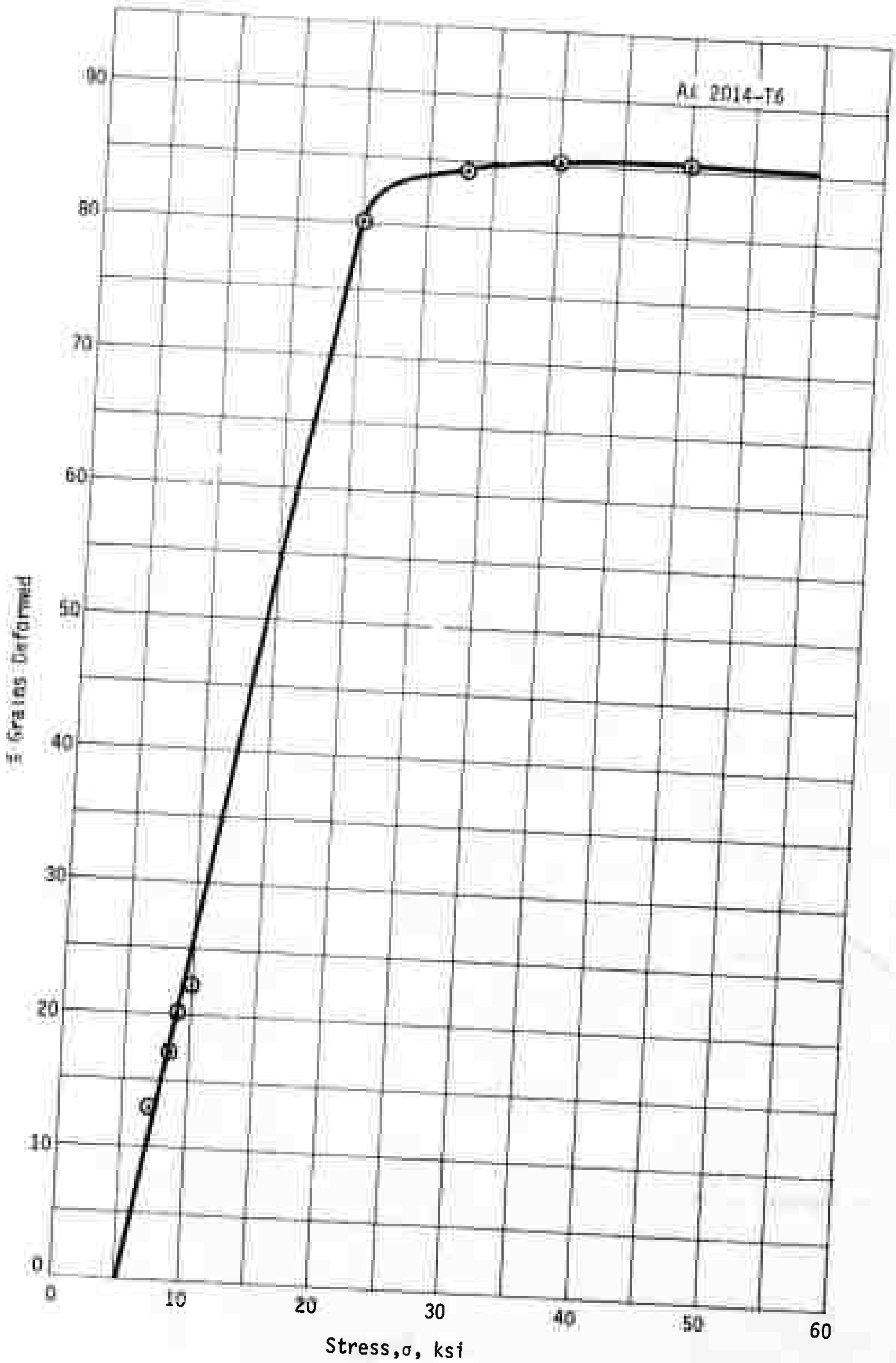


Figure 5 Deformation of Grains as a Function of Stress

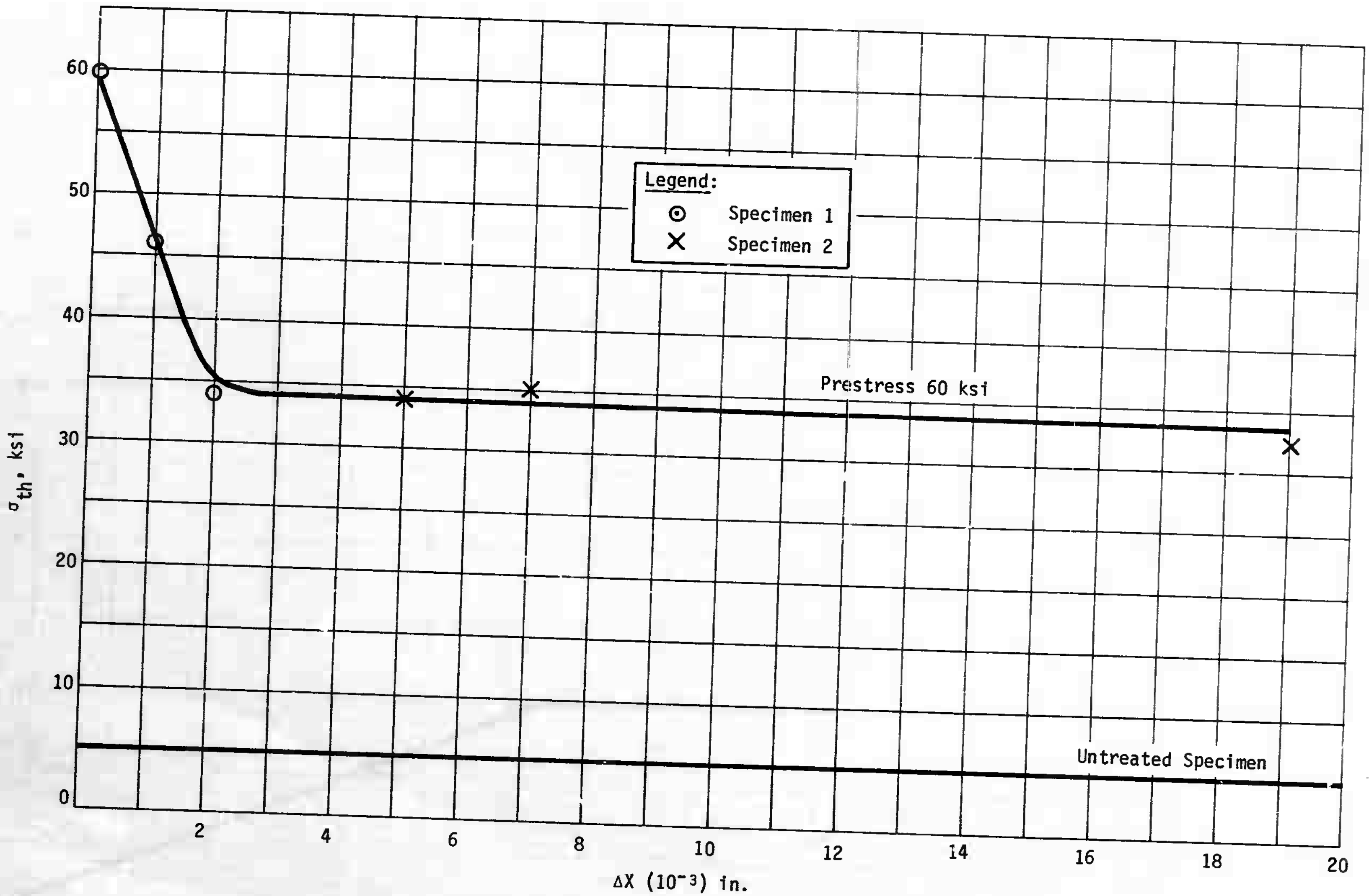


Figure 6 The Variation of the Threshold Stress for Plastic Deformation with Depth from the Surface, ΔX, for Prestress $A\ell$ 2014-T6. σ_{PS} = 60,000 psi

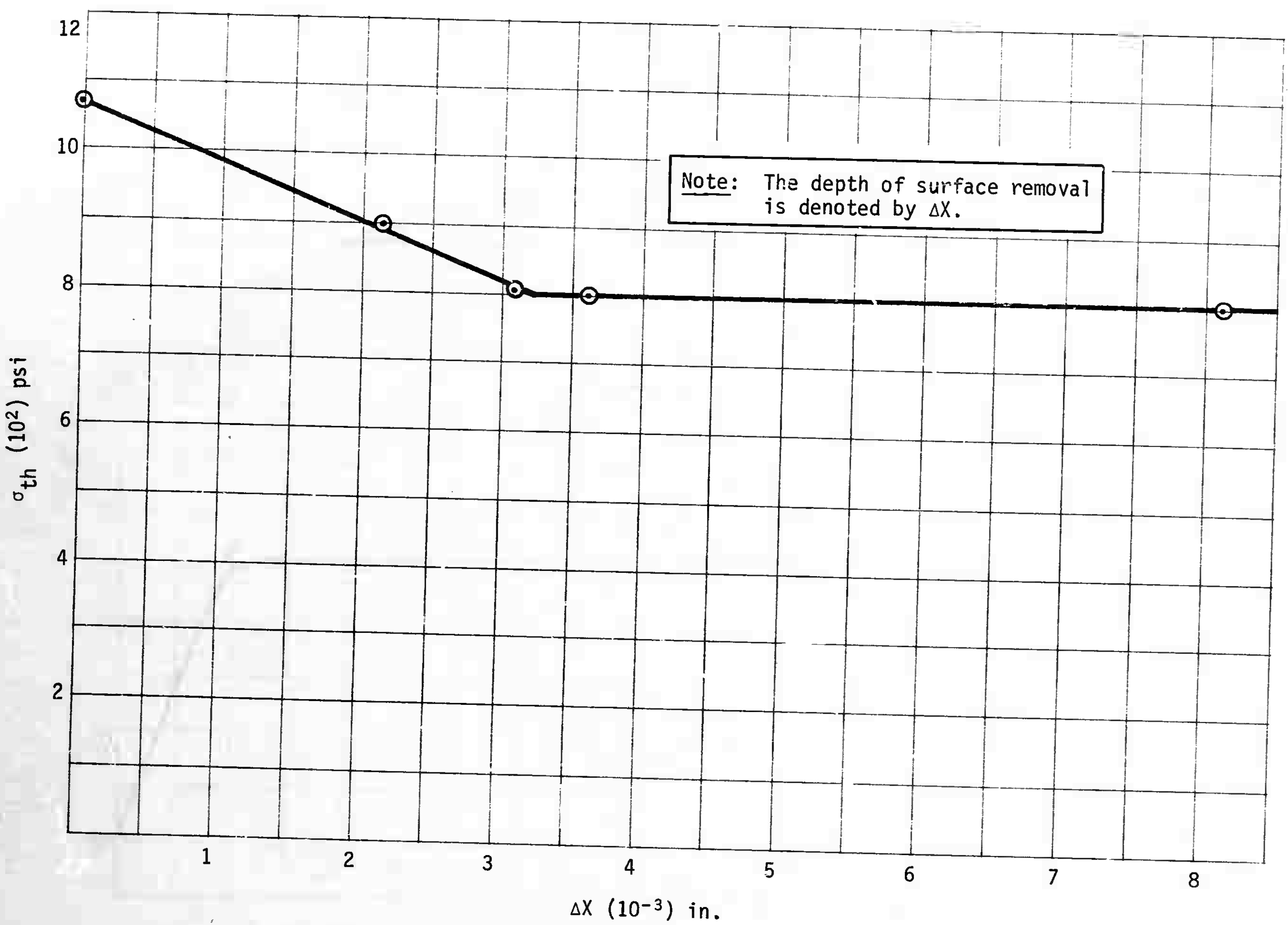


Figure 7 The Variation of the Threshold Stress for Plastic Deformation with Depth from the Surface, ΔX, for Aluminum Single Crystals. σ_{PS} = 1080 psi